Progress Report and Work Plan

on

Study of Cryogenic Complex Plasma

AOARD 064024

FA4869-06-1-0033

For the period of
April 1, 2006 to March 31, 2007

Submitted to

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14. ABSTRACT

14. ABSTRACT This Report describes the investigation entitled by ?Study of Cryogenic Complex Plasma? (Principal investigator: O. Ishihara, FA4869-06-1-0033, AOARD 064024) for the period from April 1, 2006 to March 31, 2007. The research has been carried out at Yokohama National University. Research personnel includes a senior technical advisor Dr. Yoshiharu Nakamura, a research associate Dr. Masako Shindo and a senior doctoral student Mr. Chikara Kijima. Several graduate students as well as senior students were also involved in experiments as well as theories. Two Dewar bottles, YD-1 (Yokohama Dewar 1) and YD-2 (Yokohama Dewar 2), accommodate cryogenic plasma with dust particles. The cryogenic rf plasma and complex plasma was produced in a glass tube in YD-1, although cryogenic complex plasma has not been produced yet. The cryogenic plasma has been produced in the vapor of the liquid helium in YD-2 device, but the cryogenic complex plasma has not been clearly observed in YD-2 yet. The linear device YCOPEX (Yokohama Complex Plasma Experiment) has been assembled to study the fundamental physics of room temperature complex plasma which supports the diagnostics of complex plasma to be applied to YD-1 and YD-2.

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ABSTRACT

This Progress Report and Work Plan describes (1) the research work on the contract of investigation entitled by “Study of Cryogenic Complex Plasma” (Principal investigator: O. Ishihara, FA4869-06-1-0033, AOARD 064024) for the period from April 1, 2006 to March 31, 2007, and (2) the work plan for the following year. The research has been carried out at Yokohama National University. Research personnel includes a senior technical advisor Dr. Yoshiharu Nakamura, a research associate Dr. Masako Shindo and a senior doctoral student Mr. Chikara Kijima. Several graduate students as well as senior students were also involved in experiments as well as theories. Two Dewar bottles, YD-1 (Yokohama Dewar 1) and YD-2 (Yokohama Dewar 2), accommodate cryogenic plasma with dust particles. The cryogenic rf plasma and a complex plasma was produced in a glass tube in YD-1, although a cryogenic complex plasma has not been produced yet. The cryogenic plasma has been produced in the vapor of the liquid helium in YD-2 device, but the cryogenic complex plasma has not been clearly observed in YD-2 yet. The linear device YCOPEX (Yokohama Complex Plasma Experiment) has been assembled to study the fundamental physics of a room temperature complex plasma which supports the diagnostics of a complex plasma to be applied to YD-1 and YD-2.

I. Objectives

Our overall goal is to study the cryogenic complex plasma experimentally and theoretically and to reveal novel natures of cryogenic complex plasma produced by a stable discharge above or in superfluid liquid helium.

II. Status of the Research

The principal investigator, Professor Osamu Ishihara of Yokohama National University, has been conducting the research at Yokohama National University.

Research personnel includes

(1) Dr. Yoshiharu Nakamura, who is a technical advisor for overall program,

(2) Dr. Masako Shindo, Research Associate, who is responsible for the YD-2 experiment,

(3) Mr. Chikara Kojima, a senior doctoral student who is in charge of YD-1 experiment.

And graduate students include Mr. M. Kugue, Mr. T. Maezawa, Mr. Y. Fukuda and Mr. K. Mita and four senior students include Mr. Y. Shinagawa, Mr. S. Ishihara, Mr. Ishizaki, and Mr. Mizutani. One doctoral student, Mr. T. Yamanouchi, has been involved in the computational research.

(1) YD-1 Experiment

A cryostat system including a Dewar vessel transferred from Niigata University to Yokohama National University is now called YD-1. Figure 1 shows the schematic of YD-1. An rf discharge in the helium gas in a glass tube surrounded by a cryogenic liquid (liquid nitrogen or liquid helium) in the Dewar bottle has produced stable plasma. Acrylic particles in the range of 1 to 10 μm were introduced into the plasma, forming a complex plasma. Dust particles in a complex plasma were illuminated by a green laser light sheet (532.8nm) through a slit with a width of 10 mm of the Dewar bottle. A novel technique of a prism-mirror method was established to observe dust particles illuminated by a laser light. Preliminary experiments of forming a complex plasma in the room temperature were carried out and the CCD camera enabled us to detect the formation of the Coulomb crystals as shown in Fig. 2.

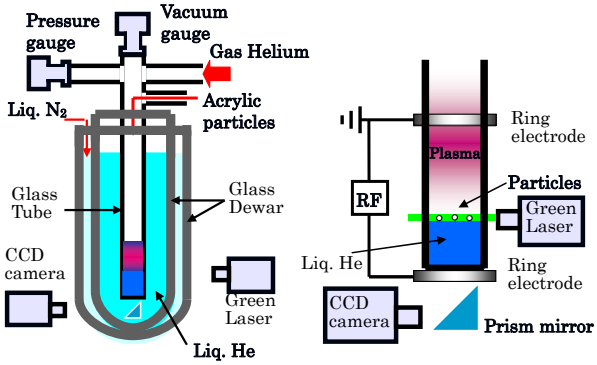

Fig. 1 YD-1 apparatus and the inner glass tube

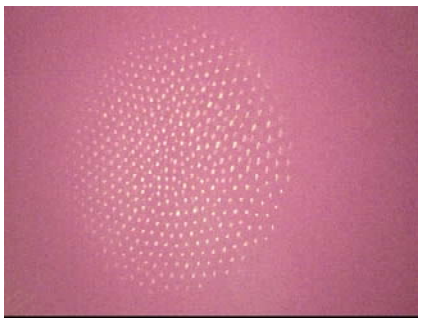

Fig. 2 CCD camera image of charged dust particles levitated and spread in a plasma in a 1.6 cm glass tube in YD-1 at 300K

(2) YD-2 Experiment

A larger Dewar vessel to accommodate a discharge chamber, build by JEC-Tori Corporation of Saitama Prefecture, is now called a YD-2 device (see Fig. 3). It was aimed to produce a plasma in a vapor of liquid helium in a confined chamber. We have produced a plasma in the vapor of liquid helium in the discharge unit with electrodes inside and tungsten wires outside of the unit. We have observed a cryogenic plasma in the device and some preliminary results with dust particles were obtained. We plan to study dynamics of dust particles in the cryogenic environment by developing a PIV (Particle Image Velocimetry) system (Ref: R.J. Donnelly et al., *The Use of Particle Image Velocimetry in the Study of Turbulence in Liquid Helium*, J. Low Temp. Phys. 126, 327(2002), E. Thomas, Jr. et al, *Experimental Measurements of Velocity Dissipation and Neutral-drag Effects during the Formation of a Dusty Plasma*, Phys. Rev. Lett. **95**, 055001 (2005)).

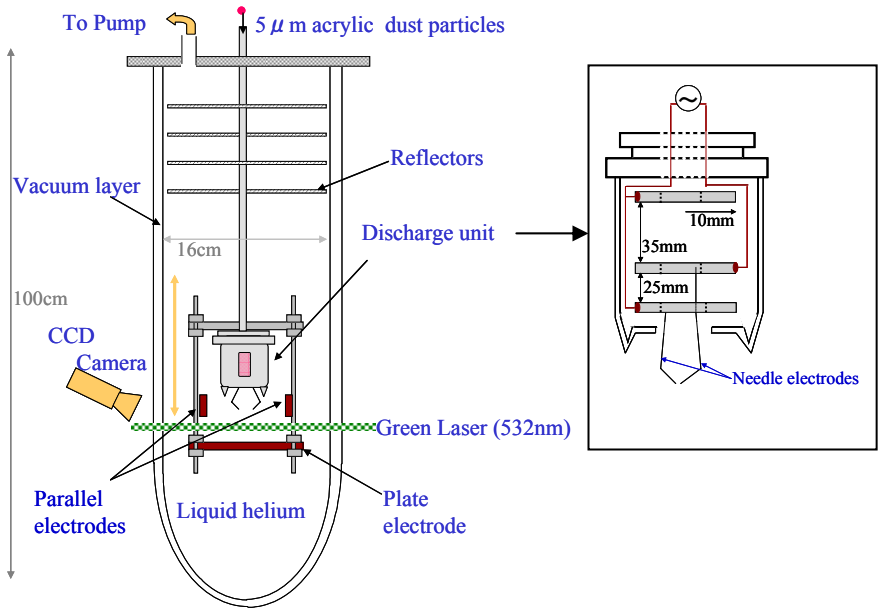

Fig. 3 YD-2 apparatus and the inner discharge unit

(3) YCOPEX (Yokohama Complex Plasma Experiment)

We have assembled a linear machine to make a complex plasma in the room temperature. This simple linear machine has been built to assist the diagnostics of a cryogenic complex plasma expected to observe in YD-1 and in YD-2. The 1 m long cylindrical Pyrex glass chamber with inner diameter of 16 cm, shown in Fig. 4 has been used to study fundamental physics of a complex plasma including charge state of dusts, ion and neutral drag forces on a dust particle, interparticle distance in a Coulomb cluster and so on. The PIV (Particle Image Velocimetry) system described in the above section to study dynamics of dust particles in a complex plasma will be tested first in YCOPEX before we can apply to a more complicated cryogenic system.

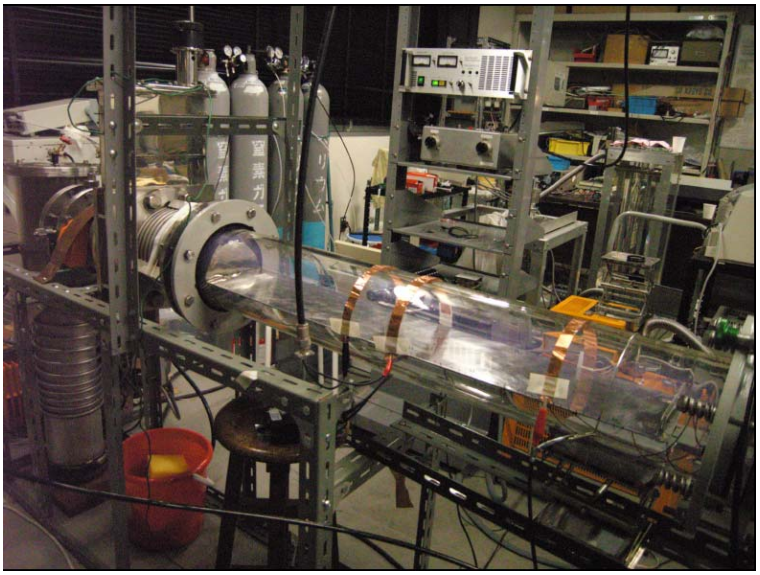

Fig. 4 YCOPEX (Yokohama Complex Plasma Experiment). Because of the observational merit, the diagnostics for a complex plasma will be developed and tested in this devoice.

(4) Numerical Simulation

Simulation of dust clusters forming in a plasma has been carried out. The CME (configuration of minimum energy) structures have been identified depending on the form of plasma confinement.

III. Publications/ Presentations

1. Publications

1. T. Yamanouchi, M. Shindo, O. Ishihara and T. Kamimura, Simulation on Cluster Structuring of Dust Particles Confined in a Plasma, Thin Solid Films **506-507**, 642-646 (2006).

2. O. Ishihara, *Coulomb Clusters in Dusty Plasmas*, in Plasma Physics Applied, edited by Crockett Grabbe (Transworld Research Network, Kerala, India, 2006), pp. 111-146.

3. O. Ishihara, Complex Plasma: Dusts in Plasma, Journal of Physics D: Appl. Phys. 40, R1-R27 (2007).

2. International Conference Proceedings

1. O. Ishihara, Attractive Force Resulting from a Free Energy in a Complex Plasma, 14th Gaseous Electronics Meeting (5-9 February, 2006, Murramarang, NSW, Australia) (Invited)

2. C. Kojima, M. Kugue, T. Maezawa, M. Shindo, Y. Nakamura and O. Ishihara, Complex plasma experiment in cryogenic environment, Proceedings of 13th International Congress on Plasma Physics, May 22-26, 2006, Kiev, Ukraine (Bogolyubov Institute for Theoretical Physics, Ukraine), E134p.

3. T. Yamanouchi, M. Shindo, O. Ishihara, and T. Kamimura, Stable and Metastable Shell Structures of a Dust Cluster in a Plasma, 11th Workshop on the Physics of Dusty Plasmas (June 28-July 1, 2006. Colonial Williamsburg, Virginia, USA)

4. O. Ishihara, Quantum Mechanical Approach to Complex Plasmas, International Workshop on Frontiers of Plasma Science (Aug. 21-Sept. 1, 2006, Trieste, Italy) (Invited)

3. Domestic Conferences

1. O. Ishihara, Frontier in dust plasmas, 2006 Annual Meeting of Japan Earth-Planetary Science Union (2006.5.14-5.18, Makuhari Messe, Chiba Pre.) U054-068 (invited).

2. C. Kojima, Y. Shinagawa, K. Mita, Y. Fukuda, M. Kugue, T. Maezawa, M. Shindo, Y. Nakamura and O. Ishihara, Dynamics of charged dust particles onn the surface of liquid heliukm, Fall Meeting, Physical Society of Japan (2006.3. 27-30, Ehime U./Matsuyama U.) 26aQB-8

3. M. Shindo, Y. Fukuda, A. Ando, C. Kojima, M. Kugue, K. Mita, Y. Nakamura and O. Ishihara, Complex plasma in the vapor of liquid helium, 23rd Annual meeting of Plasma and Fusion Research Society (2006.11.28-12.1, Tsukuba)

4. M. Kugue, Y. Shinagawa, K. Mita, C. Kojima, M. Shindo, Y. Nakamura and O. Ishihara, Behavior of dust particles on the surface of liquid helium, 23rd Annual meeting of Plasma and Fusion Research Society (2006.11.28-12.1, Tsukuba)

5. M. Shindo, C. Kojima, M. Kugue, Y. Fukuda, K. Mita, Y. Shinagawa, A. Ando, Y. Nakamura and O. Ishihara, Configuration of charged dust particles formed near the surface of liquid helium, Spring meeting of Physical Society of Japan (2007. 3.19-3.21, Kagoshima U.) 19pQE-13.

4. Theses/Dissertations

1. Yuki Shinagawa, BS March 2007

"Production of plasma and observation of dust particles near the surface of liquid helium"

Plasma is produced in liquid helium vapor in YD-2. Plasma parameters including the electron temperature and the electron density were estimated by using an electrostatic probe and optical spectroscopy. The electronic temperature and the electronic density are about 6[eV] and 10^6[cm^{-3}], respectively. Dust particles were injected near the liquid helium surface. Charged dust particles were observed to move along the electrostatic force and gravity in the plasma.

2. Takahisa Ishizaki, BS March 2007

"The experimental study on phase transition in a complex plasma"

Phase transition of a cluster of macro particles in a plasma is studied experimentally in YCOPEX. Different phases were observed in a cluster. Local phases were determined by the pair correlation function together with the kinetic temperature of macroparticles. The coupling parameter was calculated to identify the different phases.

3. Hideo Mizutani, BS March 2007

"Structure formation of Coulomb clusters in a plasma"

Numerical simulation reveals the variety of dust structures formed in a plasma.

4. Shinya Ishihara, BS March 2007

"Experimental study on interparticle distance of Coulomb crystals in a dusty plasma"

From the observation data of Coulomb crystals in a helium gas, interparticle distance of Coulomb crystals is calculated by pair distribution function.

5. Mio Kugue, MS March, 2007

"Study on cryogenic plasma with dust particles"

A new experiment of fine particle plasma under cryogenic environment was established in YD-2. Plasma is produced by a discharge in a glass tube surrounded by liquid nitrogen, and cold neutral particles could affect the behavior of electrons and ions. The observation of behavior of dust particles is used as a plasma diagnostic, and the result indicates that ions lose energy through the collisions with cold neutral particles.

6. Takaaki Maezawa, MS March, 2007

"Charge determination of dust particles by Coulomb collisions"

Charges of dust particles were determined effectively in a large volume plasma chamber YCOPEX. The charge determination depends on the Coulomb scattering observed through the CCD camera.

7. Takashi Yamanouchi, PhD March, 2007

"Numerical simulation on shell structures of a dust cluster in a plasma"

Onion-shell structures of charged dust particles in spherically symmetric electrostatic potential is studied by a dynamic particle simulation. The observed shell structures are identified as minimum energy states by the Newton optimization numerical method.

IV. WORK PLAN

1. Yokohama Dewar 1 (YD-1), a cryogenic Dewar bottle for complex plasma experiment with 9.5 cm in inner diameter and 79cm in height, uses a glass tube placed in a cryogenic liquid helium. The liquid helium of 4K at 1 atmospheric pressure (100kPa) will be cooled to the superfluid temperature of 1K as we have routinely done. In the glass tube helium gas will be filled. The temperature of helium gas in the glass tube can be cooled down to 1K by surrounding liquid helium by evaporative cooling. It is expected that the vapor pressure of the liquid helium in the glass tube is about 100 Pa at 1K. A plasma will be produced by rf discharge in a helium gas in a glass tube, while the liquid helium is also in the bottom of the tube. Acrylic powder of 1 to 10 μm is dropped into a plasma forming a dust plasma. We will form the Coulomb crystals in a tube either in the vapor or on the surface of the liquid helium. Charged dust particles are illuminated by a green laser light sheet (532.8nm) through a slit with a width of 10 mm of the Dewar bottle. Our established technique of a prism-mirror observation by CCD camera will enable us to detect the formation of the Coulomb crystals.

2. Yokohama Dewar 2 (YD-2), the second cryogenic Dewar bottle for complex plasma experiment with 16 cm in inner diameter and 100 cm in height, uses two tungsten wires exposed in the vapor above the liquid helium.

   The liquid helium of 4K at 1 atmospheric pressure will be cooled to the superfluid temperature of 1K as in YD-1. An rf plasma is produced in the vapor with a help of the discharge unit placed in the vapor. Dust particles will be introduced into the vapor. The dynamics of charged dust particles will be analyzed by taking pictures by CCD camera. Dust particles will be illuminated by red or green laser to help visualization.

   The YD-1 has an advantage to produce a stable plasma in the confined glass tube, while the YD-2 has an advantage of better observation without an extra glass tube.

3. YCOPEX (Yokohama Complex Plasma Experiment) is a large linear chamber for a complex plasma experiment at room temperature.

   The 1 m long cylindrical chamber with inner diameter of 16 cm will be used to study fundamental physics of a complex plasma including charge state of dusts, ion and neutral drag forces on a dust particle, interparticle distance in a Coulomb cluster and so on, We will develop PIV (Particle Image Velocimetry) system to study dynamics of dust particles in a complex plasma (see R.J. Donnelly et al., The Use of Particle Image Velocimetry in the Study of Turbulence in Liquid Helium, J. Low Temp. Phys. 126, 327 (2002), E. Thomas, Jr. et al, Experimental Measurements of Velocity Dissipation and Neutral-drag Effects during the Formation of a Dusty Plasma, Phys. Rev. Lett. **95**, 055001 (2005)).